ECE 371
Materials and Devices

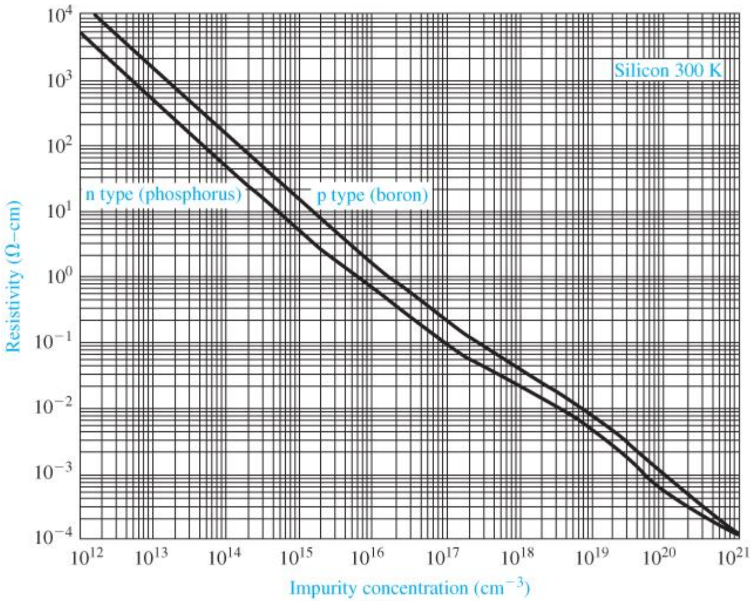
10/24/19 - Lecture 17

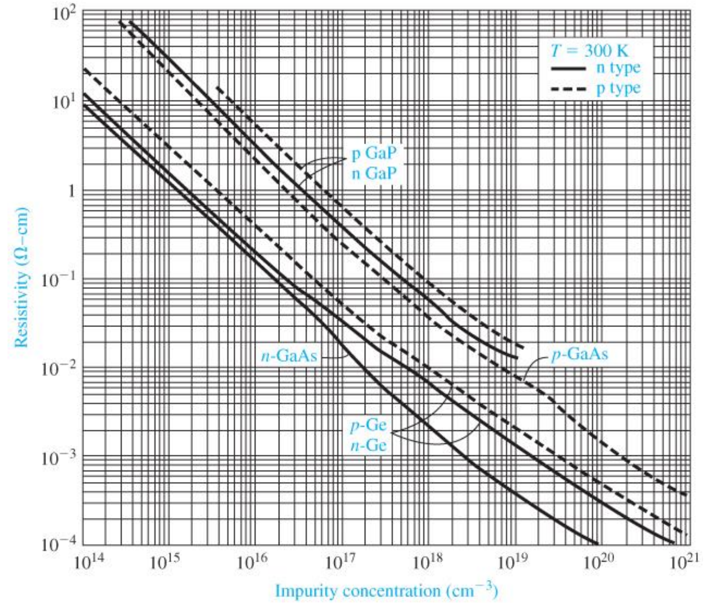
Conductivity/Resistivity, Velocity Saturation, Diffusion Current, Graded Impurity Distribution, Einstein Relation

General Information

- Homework 5 due today before class
- Homework 6 assigned and due 11/07
- Midterm #2 on 10/31, covers Ch. 3, 4, 5. Closed book, one 8.5" x 11" sheet (front and back) allowed.
- Example problems from previous midterms posted
- I will host another review session Monday 10/28 from 3:30-5:30 pm in CHTM 103. We will try to record it again.
- Reading for next time: 5.3 and 7.1 (skip Ch. 6)

Resistivity (ρ)





$$\boxed{\rho = \frac{1}{\sigma} = \frac{1}{e(\mu_n n + \mu_p p)}}$$

- σ is the conductivity
- Function of mobility and carrier concentration
- Controllable with doping
- p-type resistivity is usually higher than n-type resistivity

Relation of Resistivity to Resistance

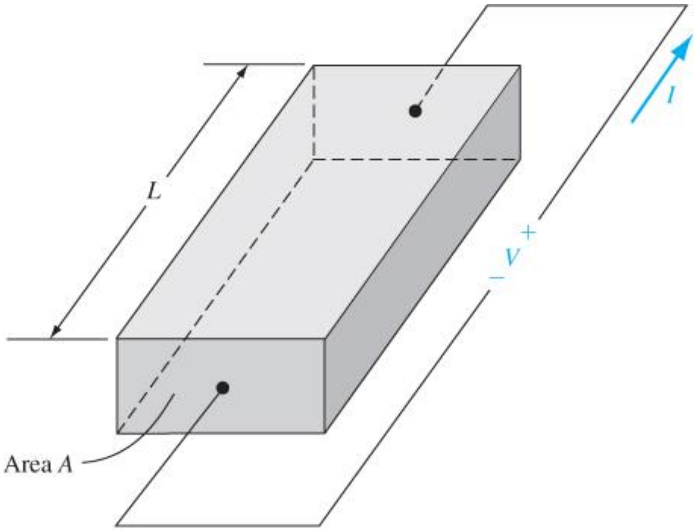


Figure 5.5 | Bar of semiconductor material as a resistor.

$$\boxed{R = \frac{\rho L}{A}}$$

- Current density: $J = I/A$
- A is the cross-sectional area
- L is the length
- Resistivity is a material property
- Resistance is dependent upon geometry

n_0 and σ vs. Temperature

conductivity depends on mobilty & carrier concentration

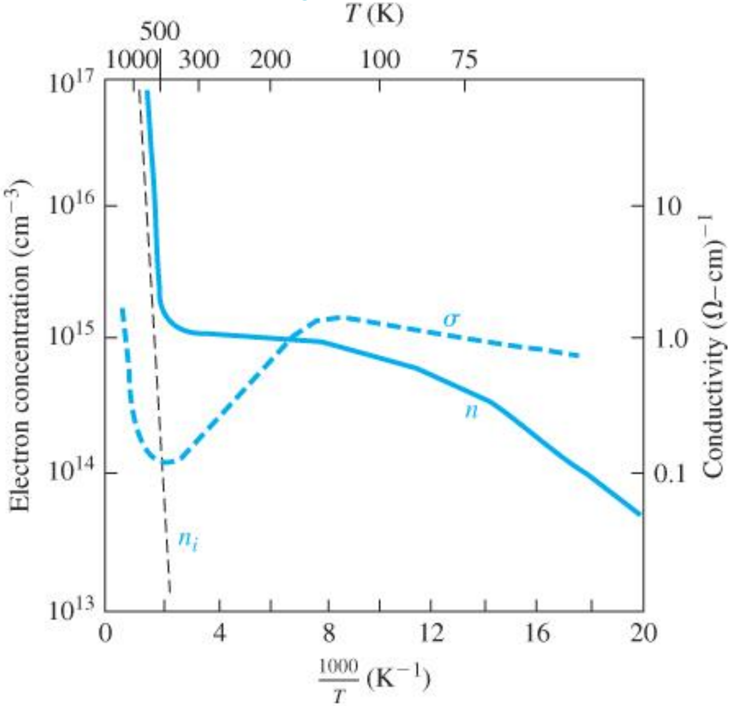


Figure 5.6 | Electron concentration and conductivity versus inverse temperature for silicon.
(After Sze [14].)

- At high T, n_i increases and dominates n_0 and σ
- Around room temperature, n_0 is almost constant (complete ionization) but σ decreases with increasing T since μ_n decreases
- At low T, freeze out begins and n_0 and σ decrease

Ex 5.3

p-type @ 300K, $N_a = 2.8 \times 10^{17}\ cm^{-3}$

$N_d = 8 \times 10^{16}\ cm^{-3}$

Find

(a) μ_p (b) σ (c) ρ

① Find $p_o = \frac{N_A - N_D}{2} + \sqrt{\frac{N_A - N_D}{2} - n_i^2}$

can reduce to $N_a - N_D$ since $N_A - N_D >> n_i$

$p_o \approx 2 \times 10^{17}\ cm^{-3} \approx N_a$

② total impurity concentration

$N_i = N_a + N_d = 3.6 \times 10^{17} cm^{-3}$

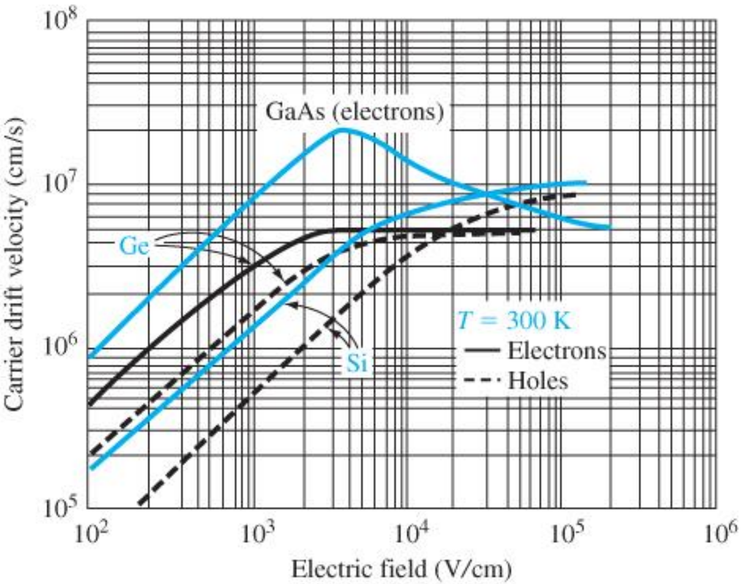
using Fig 5.3 → $\mu_p = 2.0 \times 10^2\ \frac{cm^2}{V \cdot s}$

③ $\sigma \approx e \mu_p p = (1.6 \times 10^{-19})(200\ \frac{cm^2}{V \cdot s})(2 \times 10^{17})$

$= 6.4\ \frac{1}{\Omega \cdot cm}$

④ $\rho = \frac{1}{\sigma} = 0.156\ \Omega \cdot cm$

Velocity Saturation



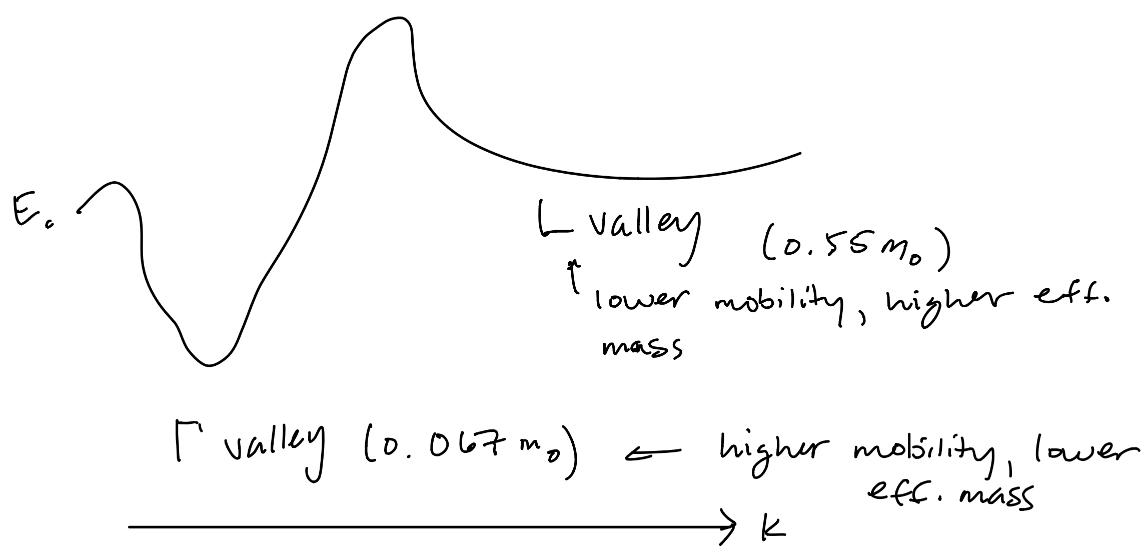
Materials	v_s (cm/s)
Si	1.0e7
GaAs	7.2e6
SiC	2.2e7
GaN	2.5e7

- Saturation velocity is the maximum velocity a carrier can attain in the semiconductor
- Determines the ultimate "speed limit" or frequency limit of transistors
- Mobility is a function of electric field at high field strengths
- When v_d saturates, so does J_{drf}
- Saturation caused by interaction with phonons

for low fields: $V_d = \mu E$ (no phonon modes)
but as E-field goes up, saturation of velocity & drift current

(mobility is function of E-field
phonon scattering (vibrating of atoms on lattice)

GaAs different – look at dispersion curve



negative differential voltage (neg. resistance)
can be used in RLC osillator devices to cancel out R

Diffusion Current Density

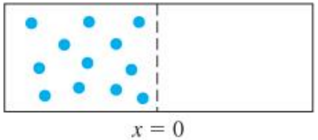


Figure 5.9 | Container divided by a membrane with gas molecules on one side.

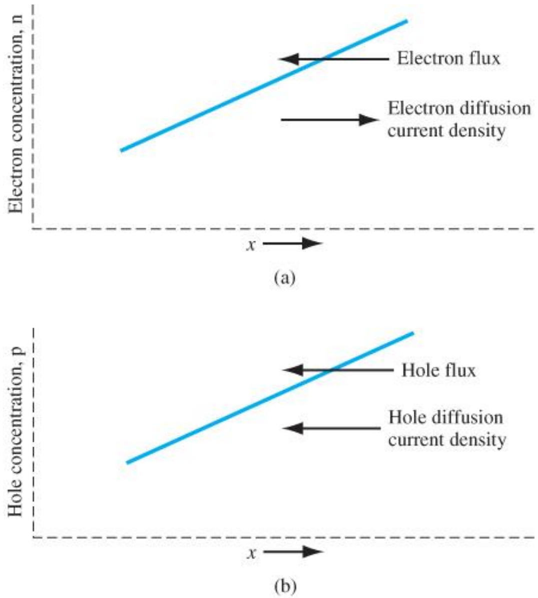


Figure 5.11 | (a) Diffusion of electrons due to a density gradient. (b) Diffusion of holes due to a density gradient.

- Diffusion: process by which particles flow from a region of high concentration to a region of low concentration

Electron and hole diffusion current densities

$$\boxed{J_{nx|diff} = eD_n \frac{dn}{dx}}$$

$$\boxed{J_{px|diff} = -eD_p \frac{dp}{dx}}$$

*units of A/cm^2

- D_n and D_p are the diffusion constants (units of cm^2/s) and quantify how well carriers move as a result of a concentration gradient
- Electron diffusion current is in the opposite direction to electron particle flux
- Hole diffusion current is in the same direction as hole particle flux

Total Current

- The total current in a semiconductor is the sum of the drift and diffusion currents for both electrons and holes

D_n = diffusion Coefficient $\left[\frac{cm^2}{s}\right]$

$$\boxed{J = en\mu_n E_x + ep\mu_p E_x + eD_n\frac{dn}{dx} - eD_p\frac{dp}{dx}} \quad \left[\frac{A}{cm^2}\right]$$

slope of electron concentration

Drift current terms that depend upon electric field

Diffusion current terms that depend upon concentration gradients

*For a given situation , we can often neglect some of the terms in the equation for total current

Test Your Understanding 5.5

TYU 5.5 The hole concentration in silicon varies linearly from $x = 0$ to $x = 0.01$ cm. The hole diffusion coefficient is $D_p = 10$ cm^2/s, the hole diffusion current density is 20 A/cm^2, and the hole concentration at $x = 0$ is $p = 4 \times 10^{17}$ cm^{-3}. What is the value of the hole concentration at $x = 0.01$ cm? (Ans. 2.75×10^{17} cm^{-3})

Graded Impurity Doping

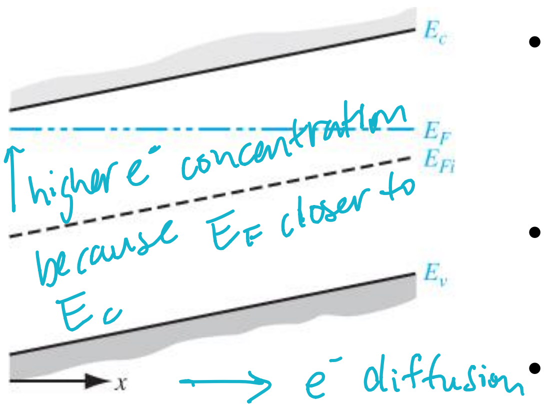


Figure 5.12 | Energy-band diagram for a semiconductor in thermal equilibrium with a nonuniform donor impurity concentration.

- Electrons on the side with higher doping concentration diffuse to the side with lower doping concentration
- After electrons diffuse, ionize acceptors are left behind
- An electric field is induced by the charge separation to oppose the diffusion process
- Quasi-neutrality is assumed so that $n_0 \approx N_d$

Fermi level flat because equilibrium

$$\boxed{E_x(x) = \frac{1}{e}\frac{dE_{Fi}}{dx}}$$

*If the intrinsic Fermi level is not constant, there is an electric field present in the semiconductor

$$\boxed{E_x(x) = -\left(\frac{kT}{e}\right)\frac{1}{N_d(x)}\frac{dN_d(x)}{dx}}$$

*Induced electric field as a function of impurity concentration as a function of x

If EFi is sloped → E-field exists

The Einstein Relation

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e}$$

- Einstein relations relate the diffusion constants to the mobilities
- Temperature dependence of the diffusion constants is the result of the temperature dependence of the mobilities (e.g., lattice and ionized impurity scattering)
- The diffusion constants are ~40X smaller than the mobilities at room temperature

Table 5.2 | Typical mobility and diffusion coefficient values at $T = 300$ K ($\mu = \text{cm}^2/\text{V-s}$ and $D = \text{cm}^2/\text{s}$)

	μ_n	D_n	μ_p	D_p
Silicon	1350	35	480	12.4
Gallium arsenide	8500	220	400	10.4
Germanium	3900	101	1900	49.2